DESY 00-081
hep-ph/0005317
May 2000

Finding η_c' and $h_c(^1P_1)$ at HERA-B

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Abstract

The production of Charmonium states η_c' and $h_c(^1P_1)$ at fixed-target experiment of pN collisions at HERA-B is considered. It is found that the HERA-B at DESY is one of the best machines in further confirming and detecting these two kinds of Charmonia in the near future.

PACS number(s): 13.60.Le, 14.40.Lb

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I. INTRODUCTION

The dramatic discovery of Charmonia, the J/ψ and its excited states, marked the beginning of a new era of particle physics. Till now the Charmonium physics remains to be one of the most exciting areas of high energy physics. As the "hydrogen-like atoms" of strong interaction, the Charmonia could be investigated partly by virtue of the perturbative QCD (pQCD) in account of the large charm quark mass, which makes the study on a relatively solid ground, as well the study may give clues of the nature of non-perturbative QCD.

Although the first Charmonium state, J/ψ, was observed more than twenty years ago, the study of the Charmonium states is still far from satisfactory. Except for the J/ψ itself, the knowledge of the other Charmonia is very limited. We do not even have a complete $c\bar{c}$ mass spectrum below the $D\bar{D}$ threshold [1], that is, the existence of the S-wave spin singlet η_c' and the P-wave spin singlet $h_c(^1P_1)$ is still based on very weak experimental signals. To confirm the existing findings and give out more precise values of the mass, width, and other parameters of these two resonances are now a pressing task in experiment.

The η_c' was first observed in the Crystal Ball experiment in the inclusive photon energy spectrum from ψ' decays at 3594 MeV [2], until now the signal was not observed by other experiments due to the low energy of the radiative photon and the relatively poor photon detection ability of other detectors comparing with that of the Crystal Ball's [3–6]. The $h_c(^1P_1)$ state was first observed at 3526.14 MeV in the proton antiproton annihilation experiment by E760 group performed at Fermilab [7], but with the statistical significance of the signal slightly more than three standard deviations, and also no other experiments definitely confirm the existence by now (the E705's report [8] was doubted by Barnes, Browder, and Tuan [9]).

Currently, the experiments suitable for Charmonium studies are: the BES detector running at the BEPC e^+e^- collider, the $p\bar{p}$ annihilation experiment represented by the E835 experiment at Fermilab, and the scarce studies of the two-photon process in high energy e^+e^- colliders like at LEP and CESR.

Due to the restriction of the quantum number at e^+e^- colliders, only the vector-like Charmonium states like J/ψ and ψ' can be produced directly at lowest order, whereas the other Charmonium states, like χ_{cJ}, η_c, and $h_c(^1P_1)$, can only be produced via either higher order processes or through the $J/\psi(\psi')$ electromagnetic and/or hadronic decays. For instance, the η_c' may be produced via $\psi' \to \gamma + \eta_c'$ and the $h_c(^1P_1)$ state via $\psi' \to \pi^0 + h_c(^1P_1)$. Although BES detector [10] has collected the largest ψ' data sample in the world, due to the limited energy resolution of the Electromagnetic Calorimeter and the rather small production rates of η_c' and $h_c(^1P_1)$ in ψ' decays, the search of either η_c' or

$h_c(^1P_1)$ did not give significant results.

As for proton-antiproton annihilation experiments, although they can produce Charmonium states of various quantum numbers and can be used to determine the resonance parameters of the Charmonium produced, the study of Charmonium is limited by the detection of the electromagnetic final states and the low production rate. The E760 and its succeeding version E835 did a very good job in measuring the resonance parameters of the χ_{c1}, χ_{c2} and some other Charmonium states, but the study on the $h_c(^1P_1)$ state is still insufficient and the existence of the η_c' is not confirmed. Of course, the E835 will continue this work and look further with more data in the near future.

The HERA-B [11], an experiment presently set up at DESY, which uses the HERA 920 GeV proton beam incident on various nuclear targets, is focused on the measurement of CP-violation in the $B\bar{B}$ system via mainly the final states containing J/ψ. The trigger system is designed to recognize events with $J/\psi \to \ell^+\ell^-$ ($\ell = e\,\mathrm{or}\,\mu$). Furthermore, the detector also is designed for precise measurement of photons with its Electromagnetic Calorimeter(ECAL), which makes the study of Charmonia very possible through detecting the final states of the Charmonium decays containing J/ψ and neutral particles like γ or π^0.

The paper is organized as follows. In following section we present the formalism for η_c' and $h_c(^1P_1)$ production in a general framework in fixed-target experiment. In section III the obtained formalism is applied to HERA-B situation numerically; the direct and indirect production rates of these two states are evaluated. In section IV, we give a rough estimation of the signals and backgrounds in searching for these two states for experimentalists' reference. In the last section some discussions and conclusions are made.

II. η_c' AND $h_c(^1P_1)$ PRODUCTION

For η_c' production, to leading order in α_s and v^2, the relative velocity of heavy quarks inside the bound state, it is a two to one process as shown in Figure 1. The parton level cross section can be easily calculated or just obtained from the corresponding η_c producing process with the non-perturbative sector replaced. It is

$$\hat{\sigma}_1 = \frac{2\pi^3\alpha_s^2}{9(2m_c)^5} < 0|\mathcal{O}_1^{\eta_c'}(^1S_0)|0 > z\delta(1-z)\ . \tag{1}$$

Here, α_s is the strong coupling constant; $< 0|\mathcal{O}_1^{\eta_c'}(^1S_0)|0 >$ is the NRQCD Color-Singlet non-perturbative matrix element, which can be related to $|R_{\eta_c'}(0)|$, the radial wave function at the origin of the bound state, by $< 0|\mathcal{O}_1^{\eta_c'}(^1S_0)|0 >= \frac{3}{2\pi}|R(0)|^2$; and $z \equiv M_{\eta_c'}^2/\hat{s}$, where $\hat{s}$ denotes the c.m.s. energy in partonic system.

As for the $h_c(^1P_1)$ production, the situation is somewhat different from that of η_c'. Of the latter, at leading order in α_s and v^2 there is only one possible channel giving the contribution, but of the former, there are several to the same order of accuracy. To be more clearly, according to the BBL theory for Quarkonium production and decays [12], the Fock states of Quarkonium are ordered in v, i.e.,

$$\left|h_c(^1P_1)\right\rangle = \mathcal{O}(1)\left|c\underline{c}[^1P_1^{(1)}]\right\rangle + \mathcal{O}(v)\left|c\underline{c}[^1S_0^{(8)}]\,g\right\rangle + \mathcal{O}(v)\left|c\underline{c}[^1D_2^{(8)}]\,g\right\rangle + \cdots . \tag{2}$$

Because for P-wave states the leading non-vanishing wave functions are the derivative of the wave functions at the origin, or in other words that the P-wave states are produced via the NRQCD dimension 8 operators or higher, the NRQCD scaling rules [13] tell us that for $h_c(^1P_1)$ production the non-perturbative matrix elements stemming from the first two terms in Eq.(2) are of the same order in v^2. Based on this argument the leading order Color-Singlet and -Octet processes of the $h_c(^1P_1)$ production are shown in Figure 2.

As depicted in Figure 2(a), the Color-Octet process is also a two to one process. The cross section of the partonic scattering process can be straightforwardly obtained,

$$\hat{\sigma}_2 = \frac{5\pi^3\alpha_s^2}{12(2m_c)^5} < 0|\mathcal{O}_8^{h_c}(^1S_0)|0 > z\delta(1-z)\ , \tag{3}$$

where $< 0|\mathcal{O}_8^{h_c}(^1S_0)|0 >$ is the Color-Octet nonperturbative matrix element.

Of the Color-Singlet processes, Figure 2 (b)-(d), the two gluon fusion channel of (b) may survive only with at least an additional gluon in the final states from the Landau-Yang theorem, as shown in the Figure; the others are not restricted by this law, however ruled out by the properties of charge-conjugation of the processes. The reason for this is that heavy-quark-loop factor (including the projector for the quarkonium state) is odd under charge conjugation. That is, the C-odd h_c state can not decay through two vector currents (C-even), and the direct calculation really shows they give no contributions. The cross section of Figure 2(b) reads as

$$\begin{aligned}
\frac{\hat{\sigma}_3(g+g\to h_c[^1P_1^{(1)}])}{d\hat{t}} = & -\frac{\pi^2\alpha_s^3 < 0|\mathcal{O}_1^{h_c}(^1P_1)|0 >}{108(2m_c)\hat{s}^2}\Bigg\{24\frac{4\hat{t}^2\hat{u}^2+\hat{s}\hat{t}\hat{u}(\hat{t}+\hat{u})+2\hat{s}^2(\hat{t}^2+\hat{t}\hat{u}+\hat{u}^2)}{(\hat{s}+\hat{t})^2(\hat{s}+\hat{u})^2(\hat{t}+\hat{u})^2} \\
& + \frac{40}{3(\hat{s}+\hat{t})^3(\hat{s}+\hat{u})^3(\hat{t}+\hat{u})^3}(12\hat{s}^6\hat{t}+44\hat{s}^5\hat{t}^2+72\hat{s}^4\hat{t}^3+72\hat{s}^3\hat{t}^4 \\
& + 44\hat{s}^2\hat{t}^5+12\hat{s}\hat{t}^6+12\hat{s}^6\hat{u}+58\hat{s}^5\hat{t}\hat{u}+149\hat{s}^4\hat{t}^2\hat{u}+179\hat{s}^3\hat{t}^3\hat{u} \\
& + 140\hat{s}^2\hat{t}^4\hat{u}+56\hat{s}\hat{t}^5\hat{u}+12\hat{t}^6\hat{u}+46\hat{s}^5\hat{u}^2+157\hat{s}^4\hat{t}\hat{u}^2+246\hat{s}^3\hat{t}^2\hat{u}^2 \\
& + 231\hat{s}^2\hat{t}^3\hat{u}^2+142\hat{s}\hat{t}^4\hat{u}^2+44\hat{t}^5\hat{u}^2+78\hat{s}^4\hat{u}^3+198\hat{s}^3\hat{t}\hat{u}^3+240\hat{s}^2\hat{t}^2\hat{u}^3 \\
& + 178\hat{s}\hat{t}^3\hat{u}^3+72\hat{t}^4\hat{u}^3+79\hat{s}^3\hat{u}^4+158\hat{s}^2\hat{t}\hat{u}^4+149\hat{s}\hat{t}^2\hat{u}^4+72\hat{t}^3\hat{u}^4 \\
& + 47\hat{s}^2\hat{u}^5+61\hat{s}\hat{t}\hat{u}^5+44\hat{t}^2\hat{u}^5+12\hat{s}\hat{u}^6+12\hat{t}\hat{u}^6)\Bigg\}\ .
\end{aligned} \tag{4}$$

Here in the above, the $\hat{s}\equiv(p_1+p_2)^2$, $\hat{t}\equiv(p_1-p_3)^2$, and $\hat{u}\equiv(p_2-p_3)^2$ are ordinary Mandelstam variables; the universal non-perturbative matrix element $< 0|\mathcal{O}_1^{h_c}(^1P_1)|0 >$ related

to the derivative of the radial wave function at original of $h_c(^1P_1)$ by $<0|\mathcal{O}_1^{h_c}(^1P_1)|0> = \frac{27}{2\pi}|R'_{h_c}(0)|^2$.

Except for the direct production of these two states given in above, another main source of their production is of the electromagnetic or hadronic decays of the ψ' in accompanying with one γ or π^0. The dominant partonic interaction processes of the ψ' production in pN collision at HERA-B energy are drawn as Figure 3.

The expression for gluon-gluon fusion processes, the Figure 3(a) and (b), can be written as

$$\hat{\sigma}_4(g+g\to\psi') = \\ \frac{5\pi^3\alpha_s^2}{12(2m_c)^5}\left\{<0|\mathcal{O}_8^{\psi'}(^1S_0)|0> + \frac{3}{m_c^2}<0|\mathcal{O}_8^{\psi'}(^3P_0)|0> + \frac{4}{5m_c^2}<0|\mathcal{O}_8^{\psi'}(^3P_2)|0>\right\} z\delta(1-z) \\ + \frac{20\pi^2\alpha_s^3}{81(2m_c)^5}(<0|\mathcal{O}_1^{\psi'}(^3S_1)|0> z^2\left\{\frac{1-z^2+2z\log z}{(z-1)^2} + \frac{1-z^2+2z\log z}{(z+1)^3}\right\}\theta(1-z)\ . \qquad (5)$$

The expression for process of Figure 3(c) is quite simple, it is

$$\hat{\sigma}_5(q+\bar{q}\to\psi'[^3S_1^{(8)}]) = \frac{16\pi^3\alpha_s^2}{27(2m_c)^5}<0|\mathcal{O}_8^{\psi'}(^1S_0)|0> z\delta(1-z)\ . \qquad (6)$$

Here, although the Octet processes are suppressed in v^2, they get compensation from the enhancement of $1/\alpha_s$ relative to the Color-Singlet process. So, it is proper to include them in the ψ' production rate estimation.

III. NUMERICAL ESTIMATION FOR η_c' AND $h_c(^1P_1)$ PRODUCTION AT HERA-B

In the above section we have calculated the necessary partonic cross sections at leading order in v^2 or/and α_s for η_c' and $h_c(^1P_1)$ production in the proton-nucleon collision. According to the general factorization theorem the experimental cross sections can be obtained by convoluting the subprocess with the parton distribution functions in the nucleons. i.e.,

$$\sigma(A+B\to C+X) = \sum\int G_a(x_a)G_b(x_b)\hat{\sigma}(a+b\to C+Y)dx_a dx_b\ , \qquad (7)$$

where the sum runs over all the possible initial interacting partons which involve in the interaction; the A and B represent nucleons; C represents the Charmonium; X and Y are the remnants of the inclusive processes; $G_a(x_a)$ and $G_b(x_b)$ are the parton distribution functions of the colliding nucleons A and B with momentum fractions x_a and x_b, respectively.

In doing the numerical estimation the following inputs are taken

$$
\begin{aligned}
&\alpha_s(2m_c) = 0.253, M_{\eta_c'} = 3.6 \text{ GeV}, M_{h_c(^1P_1)} = 3.5 \text{ GeV}, \;\; m_c = 1.5 \text{ GeV}, \\
&< 0|\mathcal{O}_8^{h_c}(^1S_0)|0 >= 0.98 \times 10^{-2} \text{ GeV}^5 \text{ [14]}, < 0|\mathcal{O}_1^{h_c}(^1P_1)|0 >= 0.32 \text{ GeV}^5 \text{ [15]}, \\
&< 0|\mathcal{O}_8^{\psi'}(^1S_0)|0 > + \frac{7}{m_c^2} < 0|\mathcal{O}_8^{\psi'}(^3P_0)|0 >= 0.56 \times 10^{-2} \text{ GeV}^3 \text{ [16]}, \\
&< 0|\mathcal{O}_1^{\psi'}(^3S_1)|0 >= 0.44 \text{ GeV}^3 \text{ [17]}, < 0|\mathcal{O}_8^{\psi'}(^3S_1)|0 >= 6.2 \times 10^{-3} \text{ GeV}^3 \text{ [17]}, \\
&< 0|\mathcal{O}_1^{\eta_c'}(^1S_0)|0 >= 0.20 \text{ GeV}^3 \text{ [18]} \;,
\end{aligned} \tag{8}
$$

and the CTEQ 3M package for parton distributions is employed with the factorization scale chosen to be equal to the NRQCD scale $\mu = 2m_c$. In making use of the present fitted matrix elements given in above, the spin symmetry relation $< 0|\mathcal{O}_8^{\psi'}(^3P_J)|0 >= (2J+1) < 0|\mathcal{O}_8^{\psi'}(^3P_0)|0 >$ has been applied.

With 920 GeV incident proton we find the magnitude of the cross sections given in the preceding section are

$$
\sigma_1 = 1076.1 \text{ nb/n}, \sigma_2 = 98.9 \text{ nb/n}, \sigma_3 = 54.8 \text{ nb/n}, \sigma_4 = 79.0 \text{ nb/n}, \sigma_5 = 5.2 \text{ nb/n} \,. \tag{9}
$$

Here, the nb/n means nb/nucleon for shorthand. The ψ' production cross section (84.2 nb/n) agrees well with the experimental measurement of $(75 \pm 5 \pm 22)$ nb/n by E789 [19], indicating the reliability of the other calculations in this paper. However, quarkonium production rates are often sensitive to the choice of m_c and the parton distributions. To see the effect of the former, we assume the difference between calculated and measured ψ' production cross sections is a pure effect of m_c, to cover the error of the measured value, m_c should vary from 1.45 to 1.65 GeV. By changing m_c from 1.5 to 1.45 and 1.65 GeV in all other cross section calculations, the relative uncertainties of the σs are shown below. As for the latter, we simply take another parton distribution functions, the GRV [20], the deviations of the σs are also listed below.

$$
\begin{aligned}
&\Delta\sigma_1 =^{+40.1}_{-44.3} +28.5 \;\% \,, \; \Delta\sigma_2 =^{+24.3}_{-46.6} +28.5 \;\% \,, \; \Delta\sigma_3 =^{+32.6}_{-55.4} +28.8 \;\% \,, \\
&\Delta\sigma_4 =^{+25.3}_{-47.7} +29.2 \;\% \,, \; \Delta\sigma_5 =^{+20.5}_{-41.4} -5.8 \;\% \,.
\end{aligned} \tag{10}
$$

Here, the first deviations come from the the change of m_c ("+" for $m_c = 1.45$ GeV and "-" for $m_c = 1.65$ GeV); the second corresponds to the choice of a different parton distribution code (GRV results relative to the CTEQ ones); We can see from the above results that the deviations of the cross sections relative to different parton distributions agree within 30%, and the charm quark mass uncertainty changes cross sections around 50%.

Due to the projected high interaction rate, 40 MHz, the results in Eq. (9) means that in a running time of 10^7s at HERA-B using the Cu target, for example, the directly produced η_c' and $h_c(^1P_1)$ events number would be about 3.3×10^{10} and 4.7×10^9. The ψ'

events number would be about 2.6×10^9, which is three orders higher than the present ψ' date sample collected at e^+e^- colliders.

Theoretical estimation of the branching fractions of the $h_c(^1P_1)$ production in ψ' decays are about $10^{-5\sim-3}$ from Refs. [21–23], and the η_c' rate are about $10^{-4\sim-3}$ from the naive estimation of the M1 transition in non-relativistic limit [24,25]. Therefore, the indirectly produced $h_c(^1P_1)$ and η_c' would be of the order $10^{4\sim6}$ and $10^{5\sim6}$ correspondingly.

The indirect production of Charmonium in B decays has been estimated in Ref. [26], the production rates of $h_c(^1P_1)$ and η_c' (assuming the same as that of η_c) are of the order of 10^{-3}. Using the $b\bar{b}$ production cross section of 12 nb/n, the produced $h_c(^1P_1)$ and η_c' events are of the order of $10^{5\sim6}$ in 10^7s of the HERA-B running time, which is the same order as via ψ' decays.

IV. SEARCHING STRATEGY

As mentioned in the introduction part of this paper, the interested topologies of detecting these two states at HERA-B are $\gamma J/\psi$ and $\pi^0 J/\psi$ for η_c' and $h_c(^1P_1)$ respectively, where J/ψ decays into lepton pairs and π^0 decays to two photons. Because of the charge-conjugation invariance, the decay modes $\eta_c' \to \pi^0 J/\psi$ and $h_c \to \gamma J/\psi$ are ruled out.

The $h_c(^1P_1)$ state was observed decaying to $\pi^0 J/\psi$ with branching ratio $\sim 10^{-3}$ [7], which is of the same order of magnitude as the theoretical expectation [21], and the η_c' decaying to $\gamma J/\psi$ is expected with a width of the order $\sim \mathcal{O}(1k\text{eV})$ [27]. Considering that the theoretical estimation of the decay width of the η_c' is about 5 MeV, it has a branching ratio of $\sim \mathcal{O}(10^{-4})$ in $\gamma J/\psi$ decay mode. Using the numbers listed above, TABLE I lists the estimation of produced events for $h_c(^1P_1)$ and η_c' in all the production mechanisms, taken into account the branching ratios of J/ψ leptonic decays and $\pi^0 \to \gamma\gamma$.

From the table, we can see the produced events of interested topologies from indirect productions are too low (of the order of 10 to 100) to produce meaningful signals for observing the two states. But instead, the direct productions of these two states are rather large, of the order of $4 \sim 6 \times 10^5$. As we know the geometric acceptance of HERA-B detector is large and its trigger is optimized for J/ψ events, we do expect high efficiency of detecting these two final states. Suppose the overall efficiency of detecting these two final states is around 10%, one expects $4 \sim 6 \times 10^4$ reconstructed events each channel, which are large numbers compared to those channels for observing CP violation (in the same running time, the reconstructed events of $J/\psi K_s$ is estimated to be around 1400!).

The main background channel for η_c' observation is $\chi_{c2} \to \gamma J/\psi$, which has the same final states but much larger cross section and very near the expected η_c' mass. Using the measured cross section of χ_{c2} by E771 [28], the number of reconstructed χ_{c2} events is

estimated to be around 10^8 (the combinational background at χ_{c2} mass region is about the same size as χ_{c2} events as shown in Ref. [28]). The significance of the observed η_c' depends strongly on the mass resolution of $\gamma J/\psi$ system and the mass difference between χ_{c2} and η_c'. Theoretical estimations of the η_c' mass ranges from 3589 to 3631 MeV [29], and only experimental hint [2] is at mass of (3594 ± 5) MeV. For a 3.6 GeV mass η_c', if the mass resolution is around 10 MeV or less, η_c' will produce a long tail at high mass side of χ_{c2}, and at mass higher than 3.6 GeV, the events is almost free from χ_{c2} background. If the mass resolution reaches 15 MeV or even larger, it will be hard to distinguish η_c' from χ_{c2}. A larger $m_{\eta_c'}$ obviously will increase the possibility of resolving η_c' from the χ_{c2} tail, while a low mass η_c' will more depend on the mass resolution.

For $h_c(^1P_1)$, the main background is from the $\pi^0\pi^0 J/\psi$ produced by ψ' decays. Compared with that in η_c' case, here the $h_c(^1P_1)$ is at the phase space limit of $\pi^0 J/\psi$ system produced from ψ' decays and the cross section of the latter is smaller than χ_{c2} by at least a factor of 3%. Furthermore, there is no other nearby resonance decays to the same final states. All these make the observation of $h_c(^1P_1)$ easier than η_c'.

At the point of data analysis, for η_c', instead of using the invariant mass of J/ψ and the detected γ, using the mass difference between the $\ell^+\ell^-\gamma$ system and the $\ell^+\ell^-$ system would be better in finding the signal, since the latter can compensate some of the effects due to energy losses of radiation and bremsstrahlung of the lepton tracks.

In searching for the $h_c(^1P_1)$ state, the reconstruction of the π^0 is also important for the event selection, and it is also a very good constraint to lower the background level greatly. As in the $\gamma J/\psi$ case, the mass difference method will be helpful to this channel as well.

Finally, to check the results, the sideband method maybe useful. In both cases the J/ψ mass sidebands, and in $h_c(^1P_1)$ searching the π^0 mass sidebands will tell us the shape of the background. The absence of the same peak in the mass spectrum of sidebands events will be a demonstration that the selection is reasonable.

It is important to note that all above discussions are based on a sample of 10^7s running time. With more statistics, instead of reconstructing photon from ECAL, one can detect converted photon to reconstruct η_c' and $h_c(^1P_1)$, as has been indicated by E771 [28]. In this case, the mass resolution will be significantly improved (5.2 ± 2.0 MeV for $\gamma J/\psi$ system in E771 experiment), η_c' will be resolved from χ_{c2} even it has a small mass.

V. DISCUSSIONS AND CONCLUSIONS

In this paper we have discussed the physics potential of HERA-B in detecting the η_c' and $h_c(^1P_1)$. Our numerical results reveal that there are about 10^{10} and 10^9 of η_c'

and $h_c(^1P_1)$ events would be produced at HERA-B in 10^7s of running time. A rough estimation shows that $h_c(^1P_1)$ will be observed clearly in its $\pi^0 J/\psi$ decay mode, and η_c' will be observed as a shoulder at high mass side of χ_{c2} in $\gamma J/\psi$ channel if the mass resolution is not too large.

The searching strategies of these two states at HERA-B are given. The major backgrounds in the detection and the possible detecting measures are also discussed.

It should be mentioned that the theoretical basement of our calculation in this paper, the NRQCD factorization, may not work well in the inclusive quarkonium production at full phase space, that is at small p_T (p_T not much greater than $\Lambda_{\rm QCD}$) region, which would cast some shadow on the validity of the results of the inclusive fix-target calculations. However, at least from our calculation on ψ' production, which agrees with the experiment value quite well, we are convinced to a certain degree of our other calculations in this paper.

Last, it should be noticed that although the study proceeded in the paper is just an order estimation because either input parameters, like the color-octet matrix elements, are more or less accurate just to an order, or the evaluation is based only on the first order calculation, or the factorization problem mentioned above, the results were well constrained by the known measurement of ψ' production, so the conclusion of the paper should hold. That is, the detection of η_c' and $h_c(^1P_1)$ at HERA-B is feasible and promising.

ACKNOWLEDGMENTS

C.-F. Q. thanks the Alexander von Humboldt Committee for financial support; C. Z. Y. thanks Prof. H. Kolanoski, Prof. C. H. Jiang and Prof. M. Davier for helpful discussions and comments.

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TABLES

TABLE I. Estimation of event numbers of $h_c(^1P_1)$ and η_c' production at HERA-B

State	η_c'	$h_c(^1P_1)$	ψ'		$b\bar{b}$		inel.
Cross section (/n)	1076.1 nb	153.7 nb	84.2 nb		12 nb		13 mb
Events rate (Hz)	3311	473	259		37		40 M
N^{prod} in 10^7s	3.3×10^{10}	4.7×10^9	2.6×10^9		3.7×10^8		4.0×10^{14}
Final states	$\gamma J/\psi$	$\pi^0 J/\psi$	$\gamma\eta_c'$	$\pi^0 h_c(^1P_1)$	$\eta_c' + X$	$h_c(^1P_1) + X$	
Fraction ($\ell^+\ell^-\gamma(\gamma)$)	1.2×10^{-5}	1.2×10^{-4}	$1.2\times 10^{-9\sim-8}$	$1.2\times 10^{-9\sim-8}$	4.8×10^{-8}	2.4×10^{-7}	
N^{prod} in 10^7s ($\ell^+\ell^-\gamma(\gamma)$)	4.0×10^5	5.6×10^5	$3 \sim 31$	$3 \sim 31$	18	89	
N^{obs} in 10^7s (Assuming $\varepsilon = 10\%$)	4.0×10^4	5.6×10^4	$0.3 \sim 3$	$0.3 \sim 3$	1.8	8.9	

FIGURE CAPTIONS

Figure 1. The leading order η_c' production process at PN collision in both α_s and v^2.

Figure 2. The generic diagrams of $h_c(^1P_1)$ production process at PN collision at leading order in v^2; (a) the Color-Octet process, (b) the Color-Singlet process.

Figure 3. The generic diagrams of ψ' production process at PN collision; (a) and (c) the Color-Octet processes at v^4 and leading order in α_s, (b) the leading order Color-Singlet process in both α_s and v^2.

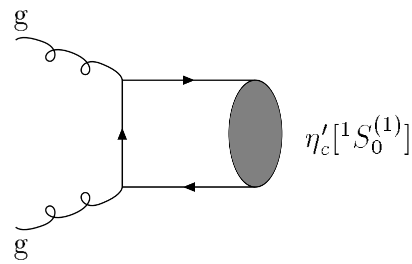

Figure 1

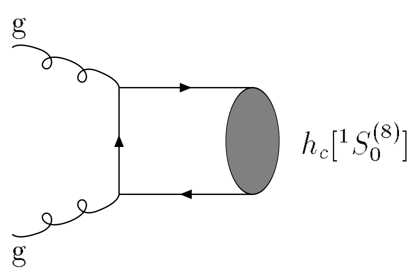

Fig. 2.a

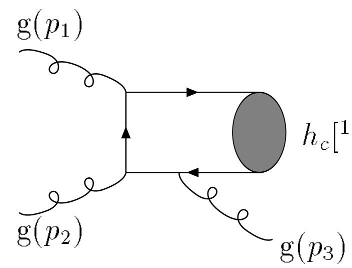

Fig. 2.b

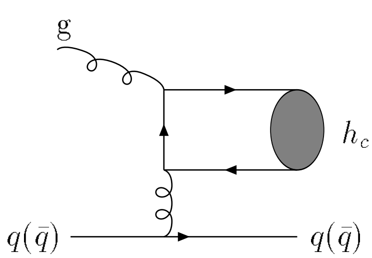

Fig. 2.c

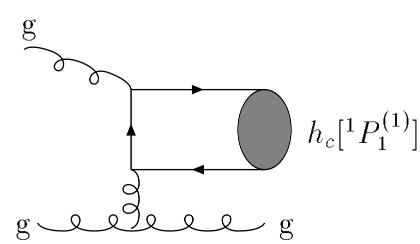

Fig. 2.d

Figure 2

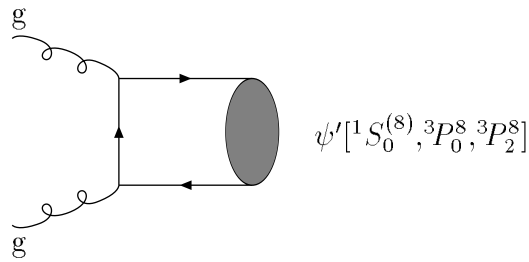

Fig. 3.a

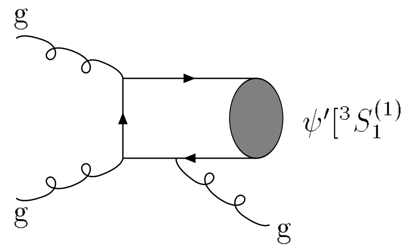

Fig. 3.b

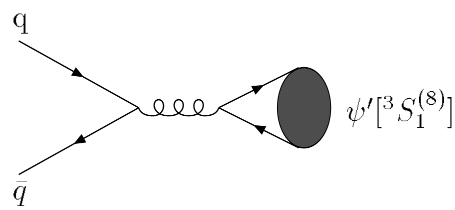

Fig. 3.c

Figure 3